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Distributed software infrastructure for evaluating the integration of photovoltaic systems in urban districts

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Abstract: Nowadays, the adoption of renewable energy sources distributed across the city is crucial for planning and developing the future *Smart City*. An accurate simulation and modelling of energy sources, such as Photovoltaic Panels (PV), is necessary to evaluate both economical and environmental benefits. With the growth of renewable sources in the city simulations of energy production became crucial for the DSO for evaluating retrofits or for network balancing events. In this paper, we present a software infrastructure for simulating the solar radiation and estimating the energy production of a district. The infrastructure simulates the PV production and evaluates the integration of such systems considering real electricity consumption data. In its core, the proposed solution models the behaviours of PV systems taking into account the digital surface of rooftops and sub-hourly meteorological data (e.g. solar radiation and temperature) to compute real-sky conditions. Then, such information is used to feed a model of the hardware components of PV systems to gain more accurate estimations of energy production in the district in real-sky conditions.

1 INTRODUCTION

Nowadays, we are moving forward to more smart and sustainable cities that aim at reducing greenhouse gas emissions. A *Smart City* approach fosters a smart energy use also taking advantage from an increasing renewable energy sources deployment. In this context, Information and Communication Technologies (ICTs) play a crucial role in both planning and monitoring of distributed energy sources. The crucial roles of ICTs and the emerging Internet-of-Things (IoT) are highlighted by the spread diffusion of heterogeneous and pervasive sensors in our houses, district and cities. IoT devices and sensors allow to collect large amounts of energy related data capable of describing the consumption behaviours of the citizens. Electricity consumption data can be used in simulation processes for evaluating: *i)* energy management actions; *ii)* management of electricity distribution networks; *iii)* integration of renewable sources in the city.

In this work, we present a methodology for developing a distributed software infrastructure to foster the usage of solar energy. Our solution exploits a Microservices approach for integrating heterogeneous sensors, services and simulation tools for evaluating the integration of Photovoltaic (PV) energy systems in urban districts. If a large amount of fluctuating energy sources are planned to be installed, an integration analysis has to be performed considering network constraints. Such analysis can be achieved correlating simulated PV systems energy production with electricity consumption data coming from IoT devices. In its core, our solution includes hardware models of PV system components to give more accurate estimations of energy production. The proposed methodology takes advantages of weather information to simulate sub-hourly real-sky solar radiation of rooftops and to analyse the hardware component performance of the PV system.

The rest of the paper is organized as follows. In

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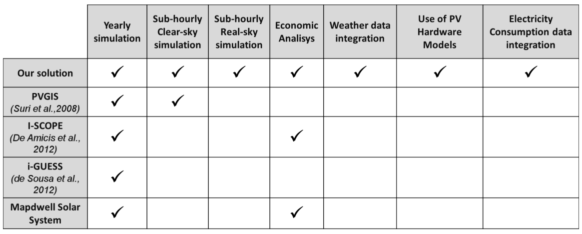
Section 2 the actual state of art of methodologies and services for PV energy simulation are presented. Section 3 analyse the motivation that prompt us to embark on this research. Section 4 presents the specifications and the methodology to develop our solution. Finally, Section 5 provides the concluding remarks.

2 STATE OF THE ART

Geographic Information Systems (GIS) tools have been applied for solar energy applications in urban context as reported by (Freitas et al., 2015). One of the major limitation of actual GIS tools consists on neglecting time domain, as reported by (Camargo et al., 2015). Both (Camargo et al., 2015; Freitas et al., 2015) highlight the fact that an accurate solar radiation estimation is needed and a detailed modelling of the components of the PV system is required.

GIS tools have been exploited also for web-based applications for fostering photovoltaic potential and system integration platforms (Suri et al., 2008; Mapdwell Solar System, ; de Sousa et al., 2012; De Amicis et al., 2012). Such platforms do not provide time-dependent simulation about energy production and PV system performances. Time dependent simulation of PV production, with an accurate evaluation of components performance, is crucial for: *ii)* planning deployment activities; *ii)* business plan evaluation; *iii)* monitoring of existing plants and smart energy use. The main limitation of such services are summarized in the following and reported in Figure 1: *i)* they provide yearly data in **real-sky** conditions; *ii)* they do not provide hourly or sub-hourly data in **real-sky** conditions; *iii)* they do not take into account PV system hardware components to model their performance and behaviour. In addition, such services do not correlate electricity consumption data with PV production simulation, which is relevant to evaluate PV systems integration.



	Yearly simulation	Sub-hourly Clear-sky simulation	Sub-hourly Real-sky simulation	Economic Analisys	Weather data integration	Use of PV Hardware Models	Electricity Consumption data integration
Our solution	✓	✓	✓	✓	✓	✓	✓
PVGIS *(Suri et al.,2008)*	✓	✓					
I-SCOPE *(De Amicis et al., 2012)*	✓			✓			
i-GUESS *(de Sousa et al., 2012)*	✓						
Mapdwell Solar System	✓			✓			

Figure 1: Confront with available services

With respect to state of the art solutions our methodology provides real-time energy production data of existing and of feasible PV systems in the district. In the simulation process, our solution takes into account also the operation efficiency of each component of the PV systems. Taking advantage of the correlation of PV energy production simulation with electricity consumption data our solution is able to evaluate the energetic impact of the integration of PV systems in the district.

3 MOTIVATION AND EXPECTED OUTCOMES

This research aims at developing a software infrastructure that exploits GIS tools, weather and electricity consumption data for evaluating PV systems integration in urban context. Our infrastructure aims at providing sub-hourly information of real-sky incident radiation on rooftops. It is devoted to both planning and monitoring phases of PV systems, spanning all scales starting from single building up to block, district and city. Such infrastructure can be exploited in order to produce forecast simulation of PV systems energy production for smart energy use. This solution is intended to satisfy the needs of different end-users such as: *i)* ***Single citizen*** can evaluate the economic and environmental savings achievable with the installation of a PV system; *ii)* ***Energy aggregators and Energy Communities*** can use the simulations to schedule consumption of their clients for maximizing self-consumption and minimizing energy bills. In particular ***Energy Communities*** can exploit such infrastructure to perform feasibility studies as proposed in our previous research (Bottaccioli et al., 2015); *iii)* ***PV system engineers*** can simulate the behaviour of converters with the application of realistic conditions. This simulation helps in dimensioning, validating and optimizing each system before and after installation; *iv)* ***Distribution system operators*** (DSO) can take advantage of the proposed solution for network balancing and for planning retrofits and/or extensions of the existing distribution grid; *v)* ***Energy and City planners*** can exploit the infrastructure for evaluating the impacts of large PV systems installations or for monitoring the performance of existing ones.

4 PV SYSTEM INTEGRATION

New methodologies and procedures for a high detailed simulations, in both spatial and temporal domains, are recently emerging in the research filed of PV potential estimation (Camargo et al., 2015; Jakubiec and Reinhart, 2013; Luka et al., 2014). These

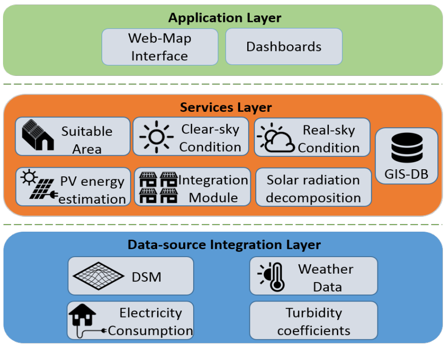


Figure 2: Distributed Software Infrastructure

works have opened the way to spatio-temporal analysis in the assessment of PV potential. In particular, (Camargo et al., 2015) highlights the necessity to integrate simulated PV production with electricity consumption data for a correct PV integration to avoid network congestions. The limitations of the state of art solution in PV energy simulation are: *i)* they run as *Desktop applications* and simulated results can not be provided easily to external users and/or other software components; *ii)* they do not integrate weather data; *iii)* they do not take advantage of hardware components models for evaluating the efficiency of a PV system; *iv)* they do not correlate PV simulated data with real electricity consumption data. Hence, the main objective of our research are: *i)* the development of a distributed software infrastructure for PV energy simulation; *ii)* the integration of the meteorological data coming from the third-party services; *iii)* the adoption of hardware components models of PV systems in order to evaluate the overall efficiency; *iv)* the correlation between PV production and electricity consumption data in order to evaluate the integration of PV systems in the district considering network constraints.

Figure 2 shows the three layers of our distributed software infrastructure. The bottom layer is the data source integration layer that is in charge of collecting the required information from the following heterogeneous data sources: *i) Digital Surface Model(DSM)*, which is a raster image that represents terrain elevation considering the presence of manufactures; *ii) Linke Turbidity coefficients* that express the attenuation of solar radiation related to air pollution; *iii) Weather data* of third party services for collecting solar radiation, temperature and wind speed; *iv) Electricity consumption data* that are used for evaluating the integration of PV systems.

The middle layer is the core of our methodology. It consists of simulation and integration services that are summarized in the following: *i) GIS-DB* stores clear-sky and suitable surface maps; *ii) Suitable area* identifies suitable surface for PV modules on rooftops; *iii) Clear-Sky simulation*; *iv) Real-Sky simulation*; *v) Solar decomposition* provides diffuse and direct components of solar radiation (as described in Section 4.2); *vi) PV energy estimation* module considers hardware components models for evaluating the performance behaviours of the PV system; *vii) PV integration* module takes into account network constraints for evaluating the integration of PV systems into the grid. Furthermore, it implements algorithm for load shifting and demand side management. The *PV integration* module performs also economic evaluation of feasible PV energy systems.

The upper layer is devoted to user applications, such as *Web-Map interface* and *Dashboards*. Both of them can provide information about performed simulation across the city with different level of details.

4.1 SOFTWARE INFRASTRUCTURE FOR PV SIMULATION

In this section, we present the methodology we are exploiting to develop our distributed simulation infrastructure for PV system planning and monitoring in a *Smart City* context. The simulation of energy production is performed taking into account the efficiency behaviours of each hardware component of the PV system. The *GIS-Server* module, showed in Figure 3, is the core of our solution. We selected the open-source software *GRASS-GIS* that provides, through *r.sun*, functionalities for computing clear-sky solar radiation. This tool has been proved to provide an accurate simulation of solar radiation in urban contexts (Ronzino et al., ; Freitas et al., 2015).

The inputs required by the clear-sky simulation process are: *i)* the Digital Surface Models (DSM) and *ii)* monthly *Linke* turbidity coefficients. In addition, the *GIS-Server* stores in its database (*GIS-DB*) pre- and post-processed data: *i)* DSM; *ii)* generated clear-sky hourly radiation maps and *iii)* suitable rooftops surface maps.

The proposed distributed infrastructure takes advantage of a Microservices approach in order to integrate different software and models in a form of interoperable services. It exploits the Web Processing Services (WPS), Web Feature Service (WFS) and Web mapping Services (WMS) that are the standards defined by the Open Geospatial Consortium (OGC). OGC specifies a service interface for publishing and performing geospatial process over the web. WPS are used for file upload and for executing the simulation process. They provide the rules for standardizing inputs and outputs of the process. WFS are used for

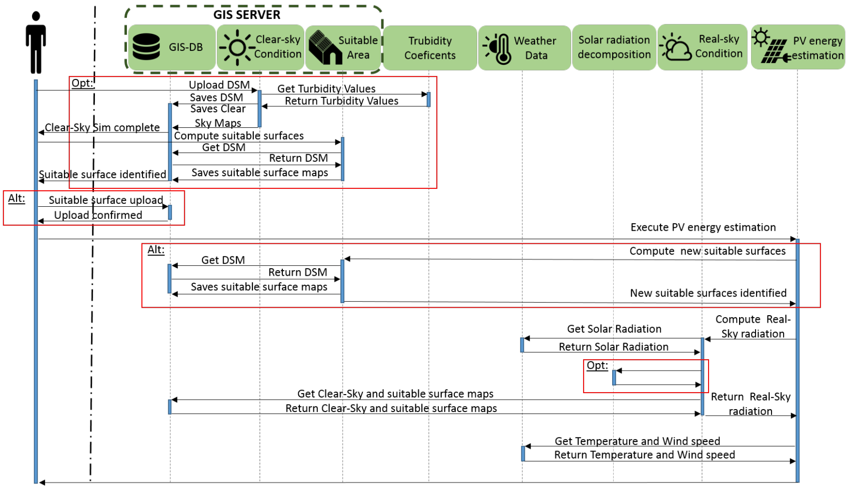


Figure 3: PV Simulation Infrastructure Time Diagram

querying and retrieving features about the elements of a polygon-map. WMS are used for the visualization of the produced map in the *Web-Map interface*.

Figure 3 shows the interactions between the software actors of our distributed infrastructure for simulating PV systems energy production and hardware components behaviours. The computation starts when the User uploads the DSM through a WPS to *GIS-Server*.The upload of the file automatically executes the clear-sky simulation module by specifying the inputs directly in request. Based on the DSM, given a date and time this process produces the related set of clear-sky radiation maps. The maps are saved in the *GIS-DB* and the User is notified. Then the User can execute the task for identifying the suitable areas for PV systems installation. This is computed by the *Suitable Surface* module that takes the DSM, slopes and orientation as inputs. The resulting maps are stored again in the *GIS-DB*. Alternatively the user can upload in the *GIS-DB* his own suitable surface maps.

Finally, the User invokes the *PV Simulation* module for estimating the energy production of a PV system exploiting also meteorological conditions. *PV Simulation* module needs the already stored information about suitable surface and clear-sky radiation maps. If new parameters for identifying suitable surface are given, such maps are re-calculated by *Suitable Surface*. Meteorological conditions are needed as well and they are provided by the nearest weather station though third-party web-services (e.g. (Weather Underground,)). In particular, solar radiation data are useful for estimating real-sky conditions by defining clear-sky indexes for both direct and diffuse radiation. Wind speed and air temperature are needed for evaluating detailed performance of each PV system hardware component (e.g. PV modules, Inverter and Maximum Power Point Tracker). Optionally, if direct and diffuse solar radiation components are not provided by third party services, the solar radiation decomposition modules is used by the simulation process. More information about weather data integration are reported in Section 4.2. The *PV Simulation* modules query the PV array data sheet in order to collect information on the PV array characteristic needed by the hardware components models.

In a nutshell, the described software infrastructure is able to simulate sub-hourly real-sky solar radiation of rooftops in a given city district area. Then it provides an estimation of PV systems energy production, also analysing its hardware components performances. Section 4.3 presents the model for energy conversion efficiency of PV hardware components, that is the core of the *PV Simulation* module.

4.2 WEATHER DATA INTEGRATION

In the last years the availability of weather station data present in our cities is strongly increased. This is due to the lower price of weather stations and the appearance of open web-services for data management and publication, such as (Weather Underground,). In order to simulate real-sky solar radiation on a pitched surface, information on direct and diffuse radiation is needed. The majority of present weather stations do not provide direct and diffuse radiation measurement, because accurate and expensive sensors would be required. In order to overcome such limitation, in our solution we have developed a module for extracting direct and diffuse radiation from global horizontal radiation. The module exploits solar radiation decomposition techniques present in the literature such as (Boland et al., 2013; Orgill and Hollands, 1977;

Erbs et al., 1982). Those experimental techniques use information only on global radiation to predict the direct and diffuse components. The user can specify which technique is the most suitable for the area of interest. This because decomposition models do not perform with the same accuracy all over the world due to their experimental nature. Indeed, depending from latitude, longitude and environmental condition the accuracy of the decomposition model can change.

This module gives to our infrastructure a big flexibility of employment due to the possibility of integrating common and available weather station data.

4.3 ENERGY CONVERSION EFFICIENCY MODELLING

Photovoltaic cells produce direct current (DC) energy at only a fraction of a volt. The utility wiring or grid and appliances within the home typically use alternating current (AC) power with voltages greater than 100V. To convert power from DC to AC, an inverter must be integrated into the PV system. Typically, another DC-DC converter is added to step up the low voltage DC produced by photovoltaic cells to the substantially higher DC voltage necessary at the input of the inverter. "Smart" converters embed Maximum Power Point Tracker (MPPT) logic that adapt the power transfer to the changing working conditions in real time.

The traditional grid-tied architecture of photovoltaic systems concentrates all the electronics in the central inverter. This is the centralized approach. To gain in terms of global system energy production, reliability, safety, communication and monitoring, the trend today is to move towards the distributed approach where the electronics is partially or fully distributed close to each panel (microinverter). In this way, the power transfer related to non-uniform shading conditions can be maximized using local MPPT.

Solar radiation and temperature have a huge influence on the characteristics and performance of each photovoltaic module, so modelling is mandatory and very useful to quantify how these environmental factors influence the performance of the system. The availability of models of the converter chain components is very important in system sizing, cost analysis, and monitoring. For a power electronics engineer working with renewable energies, it is imperative to have an accurate model as it can support testing and development of optimal solutions. At the same time, the models need to be fed with realistic input conditions taking into account solar radiation, panel location and inclination and weather data.

The authors in (Marotta et al., 2011) describe a behavioural steady-state averaged model for the solar boost converter SPV1020 by STMicroelectronics, equipped with logic running a Perturb&Observe MPPT algorithm. The same methodology is being adapted here for modelling and evaluating the efficiency of the various converters used in the district depending on their actual components and on the specific environmental conditions. It must be noted that the system engineers are more concerned with long-term behaviour than in the transients: this is the reason for which a steady-state behavioural model is employed. The rate of change of ambient temperature and insulation usually varies over minutes or hours, so slow-changing stimuli are handled. In addition, the simulation with a switching model would be extremely slow due to the prohibitively small time step needed. The behavioural steady-state averaged model is implemented to handle series and parallel connected PV panels.

4.4 ELECTRICITY CONSUMPTION DATA INTEGRATION

With the increase of *Smartness* in our cities, a large amount of IoT sensors and actuators have appeared. During this process energy monitoring and management are receiving great attention and many sensors are recording energy-related data and fluxes. Thanks to *smart-meters*, more accurate information about user energy profiles is available. Furthermore, *smart-plugs* (Ganu et al., 2012) or *Non intrusive load monitoring* algorithm (Zoha et al., 2012) provide detailed information about load consumption of each appliance. Such detailed information can be used by *Energy aggregators or Energy managers* to schedule the consumption of each user with respect to best prices or renewable production. At the same time consumption data can be use to evaluate the integration of renewable sources considering self-consumption and network constrains.

Thanks to a web-services based approach, our infrastructure allows the interaction among our solution and other distributed software architectures or services devoted to the integration of real-time data coming from the *Smart-Grid* (Patti et al., 2015; Patti et al.,). Hence, our solution is able to easily integrate data provided by *smart-meters* and/or *smart-plugs*. The integration of electricity consumption data gives us the possibility to evaluate with more detail the level of self-consumption of each user. Such detailed analysis is crucial to evaluate economics index such as *Return on Investment*, *Rate of Return* or *Pay Back Time*. Additionally, information about consumption and production profiles can be used from

Energy aggregators or Energy Communities to schedule the consumption profiles of their users for maximizing the self-consumption and the economics savings. DSOs can use consumption profile information for network balancing, active network management or for ancillary services. Finally, electricity consumption data are used to evaluate the integration of PV system in the selected area considering also the distribution network constraints.

In many areas, *smart-meters* are still not deployed and data regarding users consumption load profiles are not available. To give flexibility to our methodology, we have integrated a load profile simulation module that is able to estimate load profile with a good accuracy as reported in our previous work (Bottaccioli et al., 2015). The load profile simulation module is able to simulate the consumption profiles for different users. For residential users, the module requires information regarding the size of the houses in square meters and the number of inhabitants for each household. For industrial and commercial customers, normalized standard load profiles are used. Those standard profiles are rescaled with respect to total yearly or monthly electricity consumption.

5 CONCLUSION

In this paper, we presented a methodology for the development of a distributed software infrastructure for simulating PV system behaviours and evaluating their integration in a *Smart City* context. Combining realistic radiation modelling framework and electricity consumption data, our infrastructure can offer to users detailed information of PV energy production in real-sky conditions. With such detailed results, different users can take the optimal decisions in defining the structure and the architecture of a solar plant in an urban context, spanning all scales starting from single building up to block, district and city.

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